Woods Hole Oceanographic Institution

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PERFORMANCE CHARACTERISTICS
OF SOME WIND SENSORS

by

Richard E. Payne

December 1981

TECHNICAL REPORT

Prepared for the Office of Naval Research under Contract N00014-76-C-0197; NR 083-400 and for the National Science Foundation under Grant OCE 80-14941.

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WOODS HOLE, MASSACHUSETTS 02543

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Approved for Distribution: N.P. Fofonoff
N.P. Fofonoff, Chairman
Department of Physical Oceanography

ABSTRACT

Summaries of performance data on three wind recorder sensor sets are presented: a W.H.O.I.-built vane and cup set mounted on a vector averaging current meter (VAWR), a set of standard orthogonal propellers from the vector measuring current meter (VMWR), and an R. M. Young Company utility cup and vane set (Gill). Data were recorded in a wind tunnel and on a dock.

Cup or propeller distance constants were 14.5 m (VAWR), 11 m (VMWR), and 3.5 m (Gill). The VMWR propeller distance constant varied little with azimuth. The VAWR cups had the least sensitivity to tilt, less than 5% at 30° compared to 5% and 10% at 20° for the Gill and VMWR. The Gill and VAWR vanes had delay constants of 1.4 m and 2.6 m, damping factors of .67 and .58, and natural wavelengths of 5.9 m and 10 m, respectively, with some doubt of the VAWR vane figures due to experimental uncertainties.

That the Gill cups had the least overspeeding was apparent even in the vector averaged wind speeds from the dock intercomparisons.

In general, the Gill set is capable of recording vector averaged winds on a buoy more accurately than the VAWR or VMWR set although it is not as rugged mechanically.

ACKNOWLEDGMENTS

The technical support of Jerry Dean and Joe Poirier and other members of the Buoy Group current meter shop is gratefully acknowledged. Conversations with Bob Weller were quite helpful in setting up the experiments and understanding the data. Susan Tarbell carried out the data processing in her usual competent way.

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Introduction

Over the last decade several sets of wind measurements over the ocean have been made by Woods Hole Oceanographic Institution investigators. Most notable were measurements made in the 1972 and 1978 Joint Air Sea Interaction (JASIN) experiments (Payne, 1974, and Briscoe et al, 1979) and a twelve month data series from St. Peter's and St. Paul's Rocks in the mid-Atlantic Ocean (Garcoli and Katz, 1981).

The results of three sets of wind tunnel tests are included in this report: the 1971 static calibration of the original vector averaging wind recorder (VAWR) cups in the Wright Brothers wind tunnel (WBWT) at the Massachusetts Institute of Technology (M.I.T.), the June 1980 static calibration of the VAWR cups and vector measuring wind recorder (VMWR) propellers in the WBWT, and the September 1980 static and dynamic calibrations of the VAWR cups and vane, the VMWR propellers and a cup anemometer and vane set manufactured by The R.M. Young Company in the 5' x 7' wind tunnel (5x7WT) at M.I.T. For the speed sensors the September calibrations included absolute static calibration, calibration sensitivity to tilt, and distance constant. For the VMWR propellers, azimuthal dependence of absolute calibration ("cosine response"), distance constant and absolute static calibration were measured. For the two vanes, measurements were made to estimate damping ratio and delay distance.

In this report we also describe some environmental tests of several of the sensor sets.

Part I The wind tunnel tests

The Sensors

VAWR

In 1971 we designed and built a set of light weight cups to convert a vector averaging current meter (VACM) to a VAWR for JASIN 1972. The cups replaced the Savonius rotor in the current meter cage but the original current meter vane was used for measuring wind direction. A sketch of the rotor/vane assembly is shown in Figure 1.

The cup and vane bearings are of an open sleeve type with all parts made of stainless steel. Although these do not initially have as low friction as high quality instrument bearings, their simplicity and reliability may be suitable for long deployments at sea. During the twelve month deployment on St. Peter and St. Paul's Rocks, the bearings performed very well with little apparent wear and no systematic variations due to changing bearing friction apparent in the data.

Two types of cups have been included in our wind tunnel tests: an aluminum coated Mylar cup, Teledyne-Geotech Model 51-14531-40-10 was used in the original instrument in 1972; later Teledyne-Geotech replaced the Mylar cup with a Lexan version with the same dimensions. Cup radius is 2.6 cm and radius from the axis of rotation of the cup assembly to cup center is 8.5 cm. These dimsensions yield a rather slow rate of revolution of the cup assembly which contributes to long bearing life, but also to poor wind averages at low wind speeds due to a high threshold.

The VAWR is the original current meter vane and is made of molded plastic.

VMWR

The vector measuring wind recorder (VMWR) is a vector measuring current meter (VMCM) used as a wind recorder. Sensor configuration, two sets of double propellers mounted orthogonally on a rod referred to in this report as a "sting", is shown in Figure 2. The propellers are 22 cm in diameter and the hubs are separated vertically by 40.6 cm. The whole assembly is thoroughly described in Weller and Davis, 1980. Two sets of propellers were used, a Lexan set from the original Weller-Davis design but with .060" thick blades and mounted on an unmodified VMCM sting, and a set made of thin titanium sheet in a brass hub and mounted on a modified sting with larger diameter but smoothly rounded hub areas. This modified sting was designed by A. Ciesluk of W.H.O.I. and will be referred to as the Ciesluk sting.

Both propeller-sting sets were tested in the September wind tunnel tests but only the Lexan set in June.

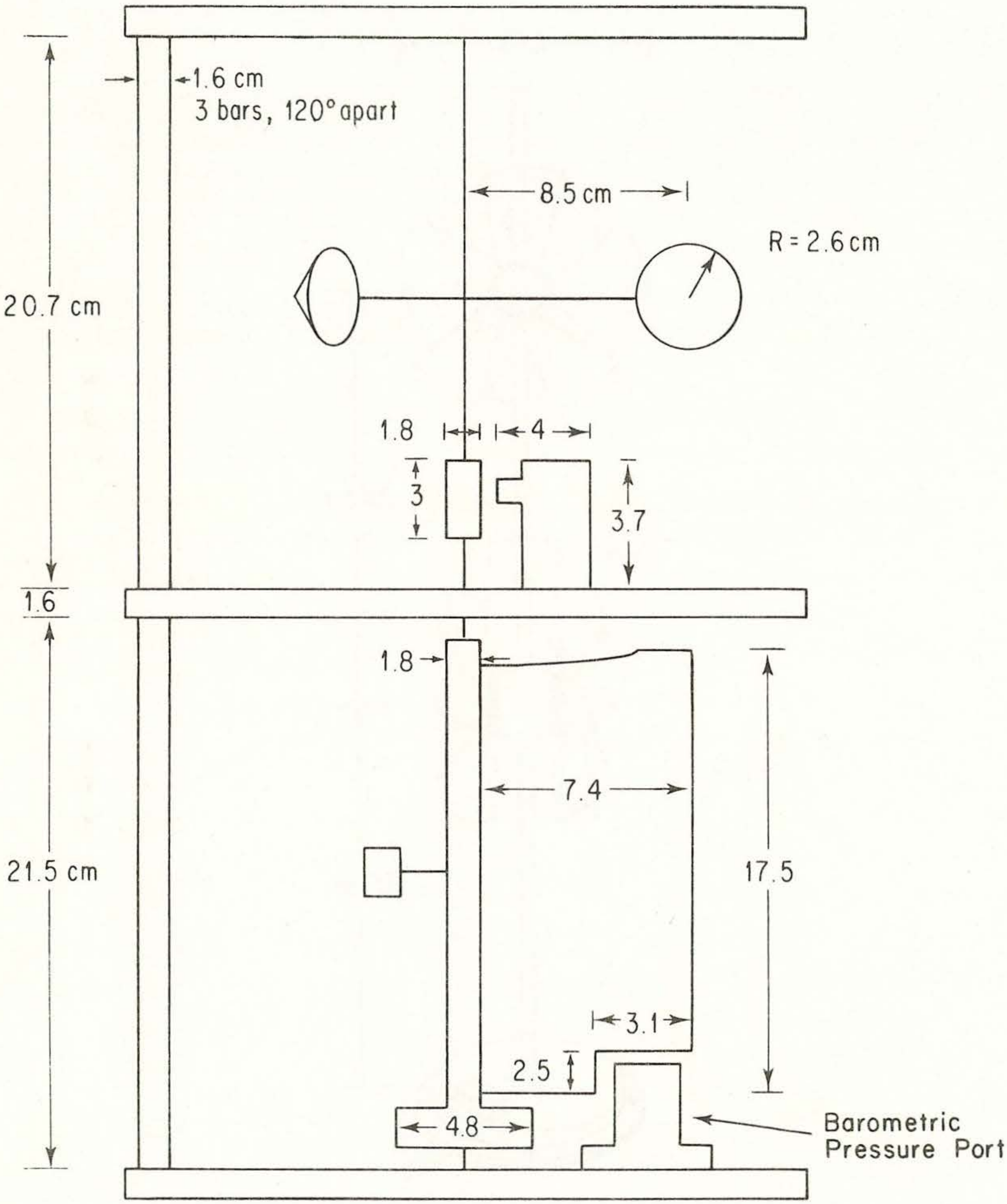


Figure 1. VAWR cup and vane cage assembly.

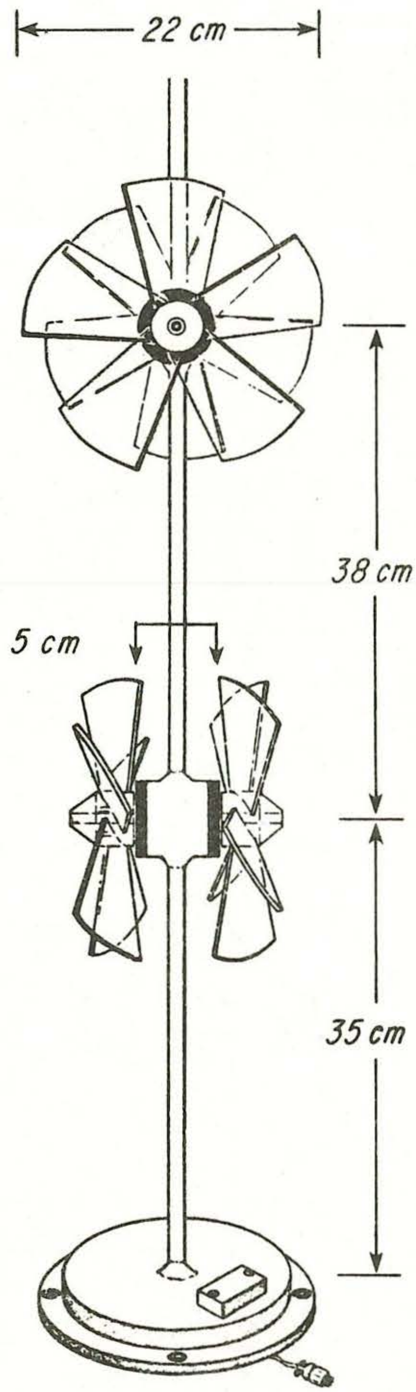


Figure 2. VMWR standard sting.

R. M. Young Company cups and vanes

After the June 1980 calibrations, two wind vane and anemometer sets were purchased from R. M. Young Company. Since the designs were developed by Professor Gill we refer to them in this report as the Gill cups and vane. These were recommended to us by Ed Michelana of the National Data Buoy Office as sets which perform well, whose characteristics are well known and which might be suitable for buoy deployment. We have used one of these sets to build confidence in our wind tunnel measurements and to compare our other sensors against. Since both sets are more sensitive than the VAWR and VMWR sensor sets they were considered as potential replacements for those sets. Both models of cup anemometers have the same cup size, 6 cm diameter, but the radius from rotor axis to cup center is different. The model 12102, the "sensitive" version, has the larger radius 6.25 cm against 4.5 cm for the Model 6101, the utility version. We purchased the light chopper rotation sensing unit instead of the more standard DC generator version for its lower threshold. For sensitive and utility versions, respectively, the distance constants are 2.4 and 3.7 m, the thresholds are .2 - .3 m s^{-1} and less than 0.7 m s^{-1} and the constant bias in the calibration curve is .3 m s^{-1} for both. The bias is related to the threshold in that the threshold is always larger.

The two vanes have the same dimensions except that the sensitive vane, Model 12302, has a thicker tail made of foamed polystyrene as opposed to the sheet aluminum tail of the utility vane, Model 6301.

Only the utility set was run through the wind tunnel tests, since it is the set we would be more likely to use in a buoy deployment. A sketch of this set is shown in Figure 3.

Wind Tunnel Facilities

Wright Brothers Wind Tunnel (WBWT)

The WBWT experiment area is in a wooden throat 7.5 feet across, 10 feet high, and 15 feet long with elliptical cross section. Speed is measured by means of a pitot tube permanently mounted in the tunnel and a combination of an alcohol manometer and an MKS Barotron pressure transducer, Type

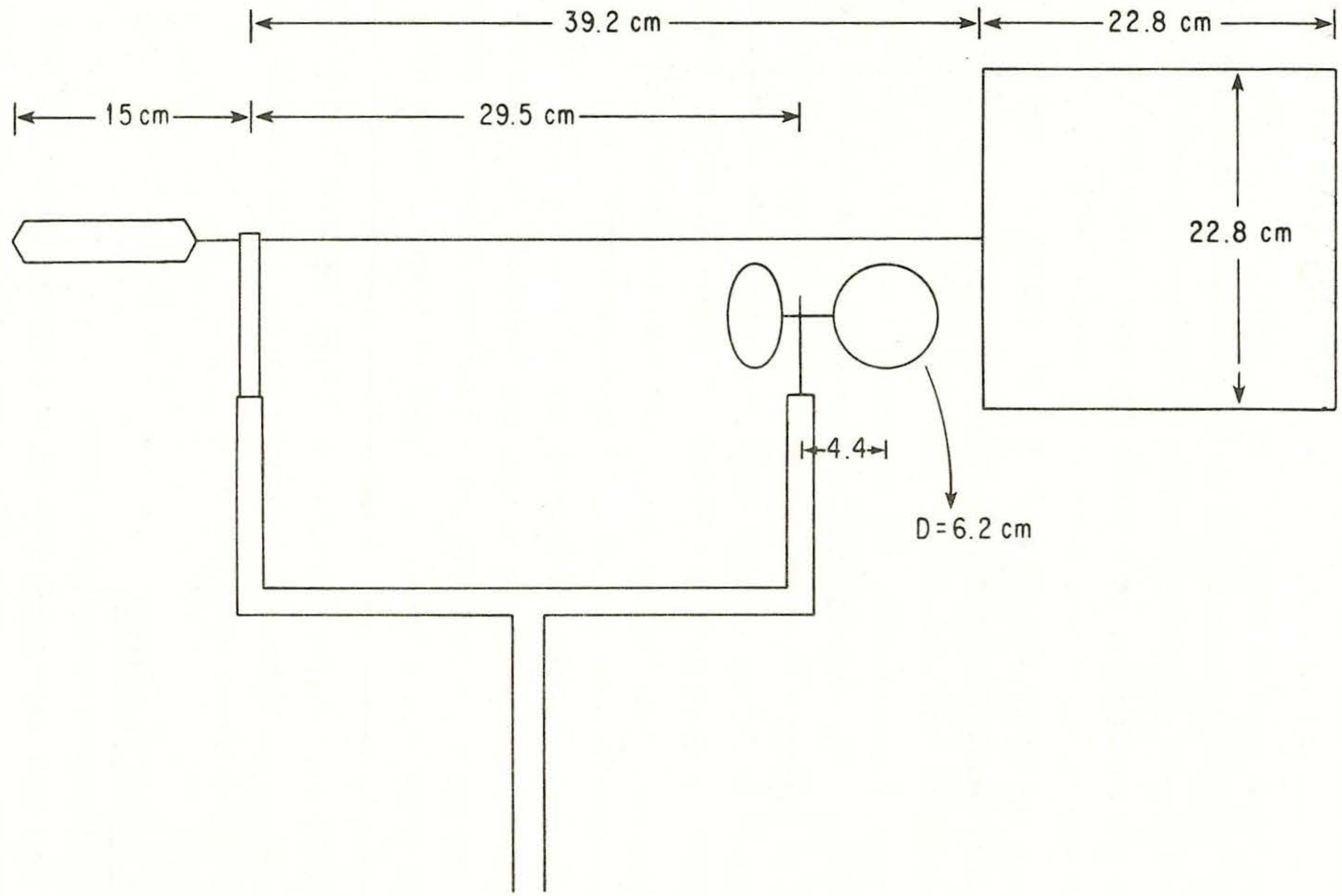


Figure 3. Gill 3 cup anemometer and vane.

170 M-6B. The Barotron had a range of 0-1 torr, equivalent to 0-14.7 m s^{-1}. The alcohol manometer was used only for speeds higher than 14.7 m s^{-1}. The expression for converting Barotron pressure P_B, in torr to wind speed in ms^{-1}

$$V = .005 + 14.737 \sqrt{P_B}$$

and for converting inches of alcohol (A) to ms^{-1}

$$V = .02 + 18.04 \sqrt{A}.$$

These equations are those used by the wind tunnel personnel and are, of course, derived from Bernoulli's equation,

$$P = \frac{1}{2} \rho V^2$$

as applied to the pitot tube. If we compute an equation analogous to the Barotron equation for typical conditions during our tests we get,

$$V = 14.757 \sqrt{P_B} ,$$

different by a negligible amount. Air temperature, humidity and barometric pressure affect the coefficient through ρ, the air density. The range of conditions we experienced over all the calibration sessions would cause variations in the coefficient of about $\pm$ 3% . This was judged small enough to ignore.

In 1972 we performed speed calibrations on two sets of Mylar VAWR cups. On 23 June 1980 we performed speed calibrations on two sets of Lexan and one set of Mylar VAWR cups and also one set of Lexan and one set of titanium VMWR propellers, both with the standard VMWR sting.

5 x 7 Wind Tunnel (5x7WT)

The 5x7WT also has a necked down portion for acceleration of flow with dimensions of 7 feet across and 5 feet high, and elliptical cross section. In the middle of the reduced area section, for a distance of about 15 feet, the tunnel walls, ceiling, and floor have been entirely removed, leaving a large area for mounting experiments. Each of our sensors was mounted on a 6" pipe pedestal in the center of this area raising it approximately to the center of the tunnel cross section.

Wind speeds were measured with a duplicate of the pitot tube used in the WBWT, also permanently mounted, and the same Barotron pressure transducer. Speeds used were less than the 14.7 m s^{-1} limit of the Barotron.

In order to measure rates of change, sensor output signals were recorded on a Sanborn recorder running at its fastest speed, 200 mm/sec. In addition, steady state signal frequencies were measured with an electronic counter.

During 8-11 September 1980 speed calibrations and distance constants were measured for one set of Lexan VAWR cups, one set of Lexan and one set of titanium propellers, the Gill cups and vane, and the VAWR vane.

Speed Calibrations

VAWR

Both the Mylar and Lexan cups have the same size and shape. Since the distance from rotor axis to cup center is also the same, we expect the slopes of the calibration curves (data in Table 1) to be the same. The y intercept may vary in time depending on bearing condition. The slope we find from all the data in Table 1 is 1.75 m-rev^{-1}. Kando et al. (1971) has predicted that the ratio of the cup speed to the wind speed will be in the range

$$.18 \leq \frac{v}{u} \leq .32$$

the precise value depending on the ratio of the normal drag coefficients of the concave and convex surfaces of the cup. The speed ratio can be expressed by

$$\frac{v}{u} = \frac{2\pi R}{A}$$

where R is the axis to cup center radius and A is the slope of the calibration curve. For our situation $\frac{v}{u} = .31$, within the range given above but near the maxium value, implying that the Teledyne-Geotech cups are quite efficient.

Using the 1.75 m-rev^{-1} value for the slope we computed a y-intercept value for each set of data and a standard deviation when the expression

$$u = B + 1.75F,$$

where B is the y-intercept and F is the rotor frequency, was least squares fitted to that particular data set. It is apparent that there is a significant variation of y-intercepts, from .4 to 1.2 m s^{-1}. Since the bearings were reasonably clean for each of these calibration runs, one would expect a larger range of y-intercepts, and therefore threshold values in a field deployment. This is not a desirable feature in an anemometer. One feature of the VAWR cup assembly which would be advantageous in field deployments is the slow rate of turning resulting from the relatively large radius from rotor axis to cup center. This would probably mean less bearing wear.

Gill 3 cup anemometer

The physical dimensions of the Gill utility cups and vane are shown in Figure 3. They were purchased only in time for the September 1980 tests in the 5x7WT. In these tests an equilibrium rotation frequency was measured at each wind speed where a distance constant run was made. The resulting data set, which appears in Table 2, did not amount to a methodical speed calibration but did allow us to confirm the manufacturer's stated constants. Our slope value of .72 m rev^{-1} and y-intercept of .2 m s^{-1} agree well with the manufacturers values of .75 m rev^{-1} and .3 m s^{-1}, respectively.

For the Gill cups the ratio of cup speed to wind speed is .37, outside the range suggested by Kondo et al. (1971). Possibly the different geometry cups placed close the rotation axis, do not fit the model on which the range is based.

VMWR - Lexan propellers on standard sting

The Lexan propellers were calibrated on the standard sting twice, in the WBWT in June 1980 and in the 5x7WT in September 1980. The data and the equations resulting from least square fits are shown in Table 3. These

Table 1
Anemometer Calibration Data
VAWR Anemometer
Wright Brothers Wind Tunnel

1972		1972		1980		1980		1980		1980		5x7WT 1980	
Mylar No. 1		Mylar No. 2		Mylar No. 3		Mylar No. 3		Lexan No. 1		Lexan No. 2		Lexan	
Wind Speed	Rotor Freq.	Wind Speed	Rotor Freq.	Wind Speed	Rotor Freq.	Wind Speed	Rotor Freq.	Wind Speed	Rotor Freq.	Wind Speed	Rotor Freq.	Wind Speed	Rotor Freq.
(ms^{-1})	(Hz)	(ms^{-1})	(Hz)	(ms^{-1})	(Hz)	(ms^{-1})	(Hz)	(ms^{-1})	(Hz)	(ms^{-1})	(Hz)	(ms^{-1})	(Hz)
5.49	2.87	2.97	1.39	2.6	.97	3.3	1.23	1.2	.37	1.3	.28	2.5	1.06
3.14	1.59	5.36	2.73	5.7	2.70	4.9	2.08	2.6	1.15	2.6	1.21	2.4	1.05
9.36	5.02	8.81	4.69	8.6	4.17	7.6	3.77	4.2	1.92	4.9	2.08	3.7	1.85
12.25	6.73	12.13	6.56	11.0	5.52	10.4	5.21	4.9	2.41	7.2	3.51	3.7	1.87
15.67	8.69	15.79	8.68	13.5	6.94	12.1	6.06	5.9	2.90	9.7	4.85	6.3	3.33
19.81	11.15	20.09	11.13	15.6	8.33	13.8	7.04	7.2	3.57	11.9	6.21	4.3	2.13
24.51	13.81	24.51	13.62	16.9	9.01	15.0	7.94	8.7	4.35	13.4	7.04	4.2	2.08
30.42	17.17	30.33	17.02	17.9	9.70	16.7	8.85	10.0	5.05	14.4	7.69	2.2	.89
						19.1	10.31	11.3	5.68	15.7	8.40	2.2	.88
						20.5	11.11	12.5	6.45	17.9	9.71	.6	
						21.7	11.76	13.9	7.41	19.4	10.75	.09	
								15.2	8.06	21.8	12.05		
								16.4	8.77				
								17.4	9.43				
								19.3	10.53				
								20.4	11.36				
Spd = .48 +	1.742F	Spd = .59 +	1.752F	Spd = 1.08 +	1.756F	Spd = 1.74 +	1.740F	Spd = .82 +	1.766F	Spd = .99 +	1.739F	Spd = .68 +	1.677F
y-intercept	.48		.59		1.08		1.74		.82		.99		.68
Std.Slope	1.74		1.75		1.76		1.74		1.77		1.74		1.68
S.D.	.08		.04		.18		.49		.23		.22		.06

Overall
Speed = .85 + 1.750F
S. D. = .10

Table 2

Anemometer Calibration Data

R. M. Young Co. Model 6101 3-cup Anemometer

Wind Speed (ms^{-1})	Rotor Frequency (Hz)
4.30	5.587
4.28	5.71
7.07	9.62
7.07	9.43
4.73	6.250
4.73	6.250
4.71	6.250
2.76	3.546
2.76	3.571
2.76	3.534

$$\text{Spd} = .21 + .720\ F$$

$$\text{S.D.} = .06\ \text{m s}^{-1}$$

Table 3

Anemometer Calibration Data

VMWR Lexan Propellers on Standard Sting

WBWT		5x7WT	
Wind Speed (ms^{-1})	Rotor Freq. (Hz)	Wind Speed (ms^{-1})	Rotor Freq. (Hz)
1.8	3.3	1.40	3.60
4.0	10.4	1.40	3.73
5.8	16.7	2.24	6.60
6.9	20.0	2.34	6.55
7.5	22.2	3.40	9.77
8.9	27.8	3.33	9.48
10.7	33.3	3.40	9.77
11.9	37.0	3.40	9.84
12.9	41.7	4.30	12.63
		4.28	12.50
		2.43	6.41
		2.43	6.51
		7.31	21.24
		7.31	21.28

V = .95 + .291F	V = .15 + .335F
S.D. = .12 ms^{-1}	S.D. = .07 ms^{-1}

Overall

Spd = .48 + .308 F

S.D. = .20

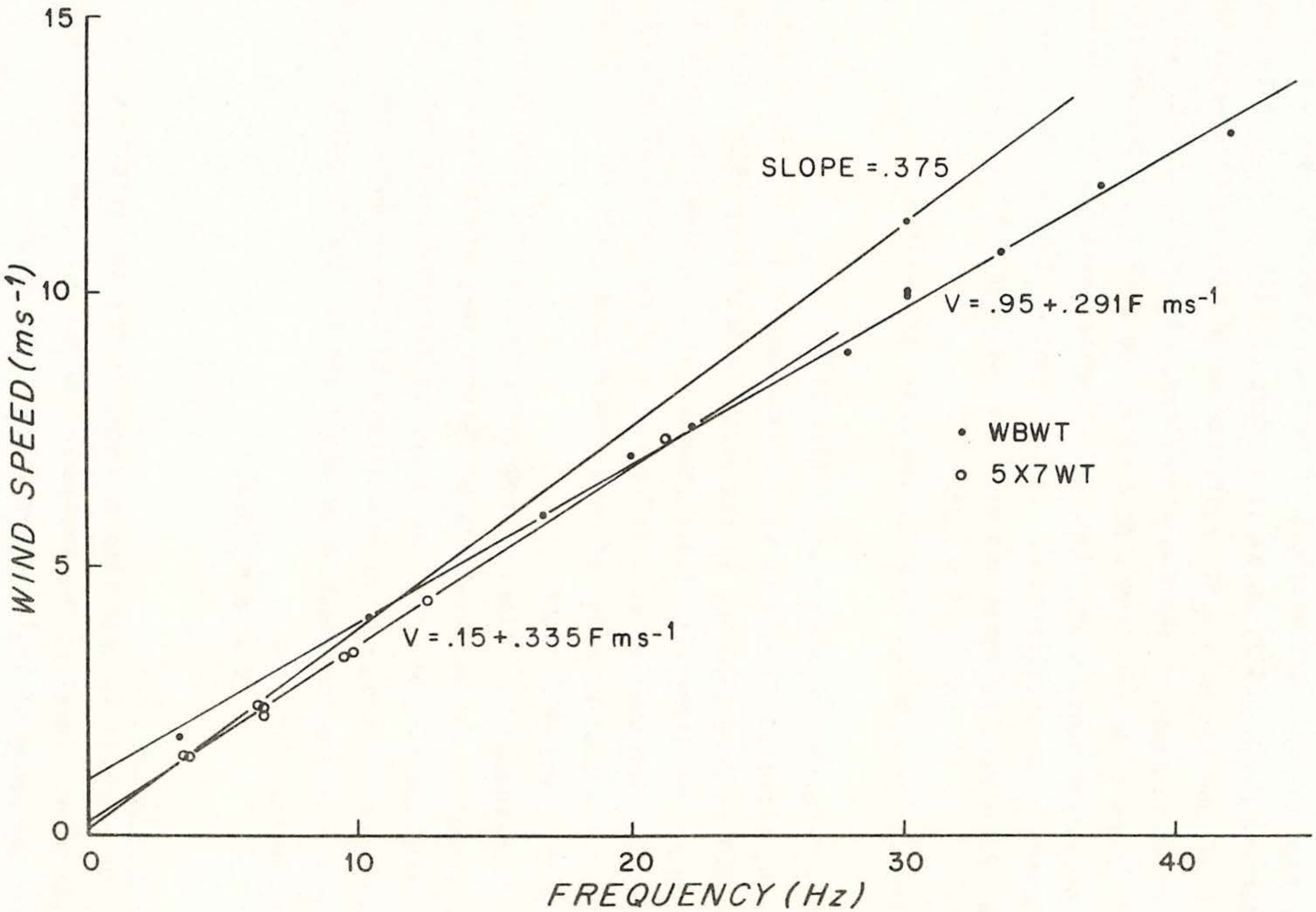


Figure 4. VMWR Lexan propeller calibration.

results are puzzling but, as the plots of the data and equations in Figure 4 show, the data really are quite different. Also puzzling is the fact that in their calibrations of near-duplicates of these propellers Weller and Davis (1980) obtained a slope of .375 m-rev^{-1}, also shown on Figure 4, and saw only a 5% variation while varying along-axis separation and relative phase of the two propellers. One possible explanation for the WBWT values is an electronic problem we had with the interface box between the propeller sensors and electronic counter which forced us to measure the frequency on an oscilloscope. In the light of this we shall consider the 5x7WT value more reliable and will use the equation

$$V = .15 + .335F$$

as the calibration equation for the Lexan propellers.

VMWR – Titanium propellers on Ciesluk Sting

The titanium propellers were calibrated on the Ciesluk sting twice in the WBWT in June 1980 and in the 5x7WT in September 1980. The data and the equations resulting from least squares fits are shown in Table 4 and Figure 5. The smaller standard deviation from the 5x7WT data may only reflect the smaller range of wind speeds used. The fit to all the data is as good as the WBWT alone.

Even though the titanium propellers do not have precisely the same dimensions as the Weller-Davis propellers they are close enough so that it is again puzzling why the slopes are so different, .260 vs. .375 m s^{-1}. The different sting design is unlikely to have an appreciable effect.

The calibration equation we shall use for the titanium propellers on the Ciesluk sting is:

$$V = .8 + .260F.$$

Sensitivity to tilt

Of interest in operation on buoys is the sensitivity to tilt of the anemometer. Ideally, the anemometer output would be independent of tilt over the range of angles experienced by the buoys.

All four anemometers were mounted, in turn, in the 5x7WT on a plank which could be inclined into or away from the wind.

Table 4

Anemometer Calibration Data

VMWR Titanium Propellers on Ciesluk Sting

WBWT		5x7WT	
Wind Speed (ms^{-1})	Rotor Freq. (Hz)	Wind Speed (ms^{-1})	Rotor Freq. (Hz)
1.2	1.72	4.67	15.11
2.5	5.88	4.67	15.20
3.9	11.4	3.55	11.19
5.0	15.2	3.55	11.24
6.8	22.2	2.51	7.68
9.8	32.3	2.51	7.56
11.2	38.5	4.43	14.19
12.9	45.5	4.43	14.13
13.7	50.0	2.51	7.57
14.6	54.1	2.47	7.53
15.3	57.1	4.73	15.39
16.2	58.8		
16.8	62.5		
17.9	66.7		

$V = 1.1 + .254F$ $\quad$ S.D. = .24 ms^{-1}

$V = .32 + .288F$ $\quad$ S.D. = .02

All Data

$V = .8 + .260F$

S.D. = .24 ms^{-1}

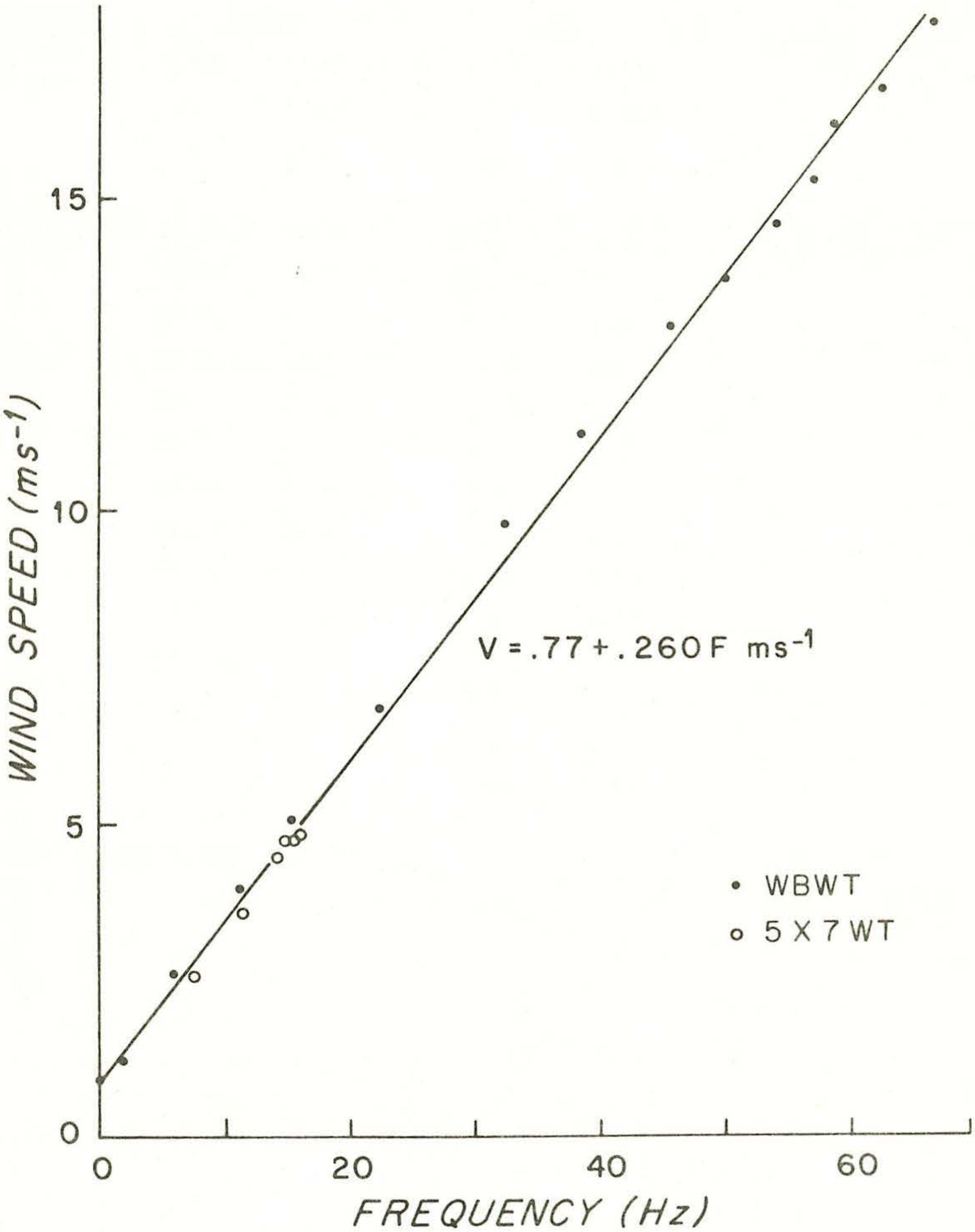


Figure 5. VMWR titanium propeller calibration.

Gill

For angles less than 40°, the Gill anemometer response was within 10% of the response at no tilt. The results are listed in Table 5 and plotted in Figure 6 for two wind speeds, 4.3 and 7.1 m s^{-1}. The cosine of the tilt angle is included for reference.

Table 5
Inclination Sensitivity
Gill Anemometer

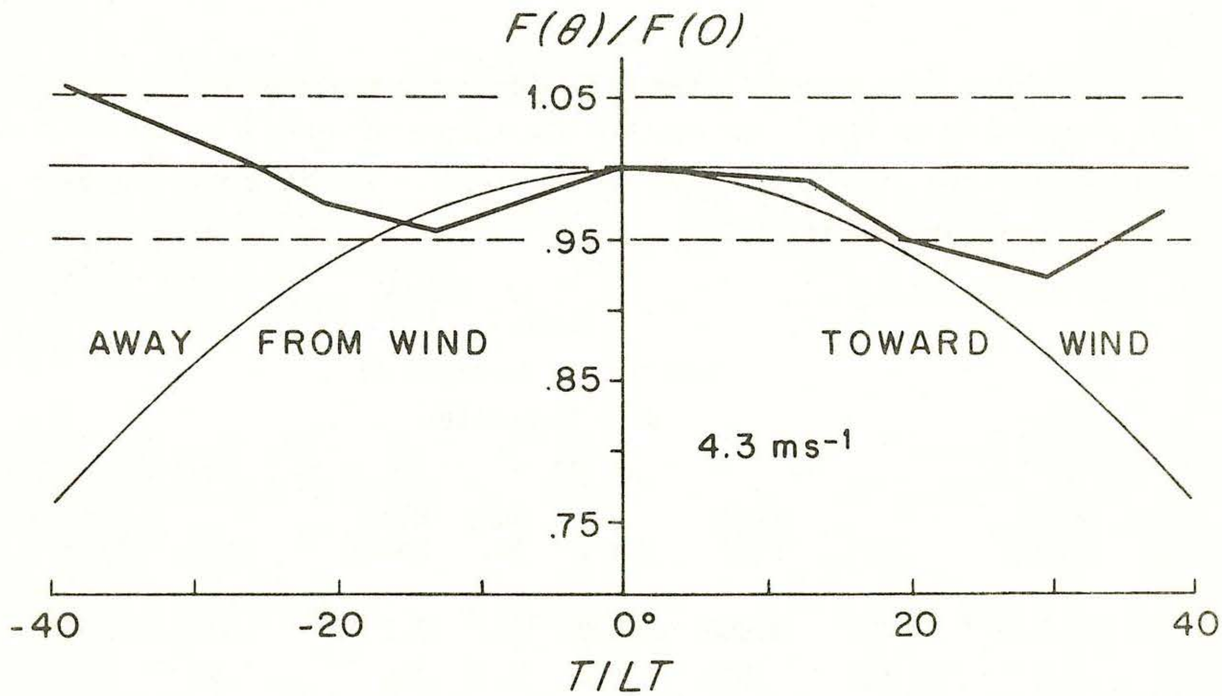
Run No.	Wind Speed	Incl.	$\frac{F(\theta)}{F(0)}$	Cos θ	Run No.	Wind Speed	Incl.	$\frac{F(\theta)}{F(0)}$	Cos θ
38	4.3 ms^{-1}	0°	1.000	1.000	40	7.1 ms^{-1}	-38	1.040	.788
	4.3	13	.990	.974		7.1	-25	.990	.906
	4.3	20	.947	.940		7.1	-16	.991	.961
	4.3	30	.922	.866		7.1	-10	.991	.985
	4.3	37	.963	.799		7.1	0	1.000	1.000
39	4.3	0	1.000	1.000	41	7.1	0	1.000	1.000
	4.3	-13	.956	.974		7.1	13	.982	.974
	4.3	-21	.974	.934		7.1	21	.947	.934
	4.3	-26	1.000	.899		7.1	32	.923	.848
	4.3	-39	1.056	.777		7.1	39	.947	.777

For tilts less than 20°, the maximum we expect from discus buoys, the Gill anemometer varies less than 5% from its response when vertical.

VAWR

The experimental results for wind speeds of 6.17 and 4.25 ms^{-1} are listed in Table 6 and plotted in Figure 7.

Frequencies in Run No. 37 were adjusted for tunnel wind speed variations of up to .05 ms^{-1} from nominal value. This affects the plotted response ratio by a maximum of .01.



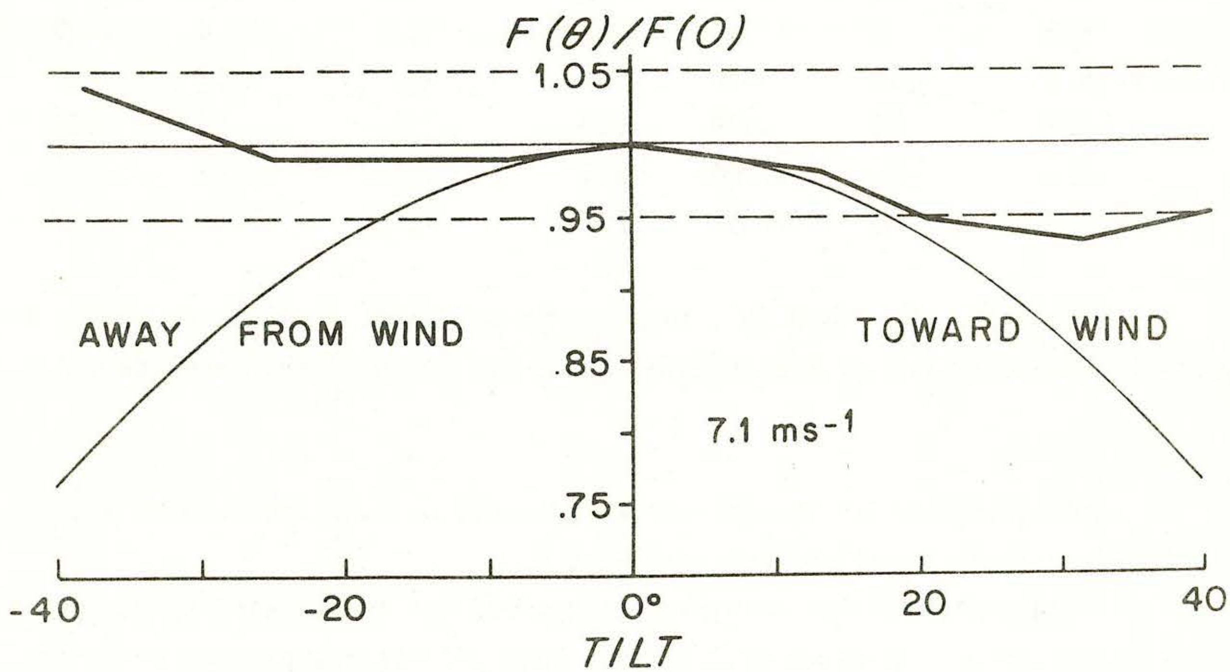


Figure 6. Inclination sensitivity of Gill anemometer.

Table 6
Inclination Sensitivity
VAWR Anemometer

Run No.	Wind Speed	Incl.	$\frac{F(\theta)}{F(0)}$	Cos θ	Run No.	Wind Speed	Incl.	$\frac{F(\theta)}{F(0)}$	Cos θ
36	6.17 ms^{-1}	0°	1.000	1.000	37	4.25 ms^{-1}	0°	1.000	1.000
	6.17	11	.994	.982		4.25	-12	1.034	.978
	6.17	17	.991	.956		4.25	-19	1.024	.946
	6.17	32	.997	.848		4.25	-31	1.023	.857
	6.17	-4	.991	.998					
	6.17	-11	1.052	.982					
	6.17	-20	1.012	.940					
	6.17	-25	1.003	.906					
	6.17	-35	.991	.819					
	6.17	0	1.000	1.000					

The VAWR anemometer appears to be less sensitive to tilt than the Gill, probably because the plates above and below the cups tend to channel the flow.

VMWR - Weller sting and Lexan propellers

The upper and lower propellers were tested separately but were only inclined into the wind. The data appear in Table 7 and Figure 8. Differences between actual and nominal wind speed for each data point were within the speed accuracy of the tunnel sensor so no corrections were made. This shows up in the two 0° points for 2.70 ms^{-1} in Run Number 19. Since there is no apparent correlation with wind speed or upper or lower propellers, the scatter between the plotted points probably represents experimental uncertainty.

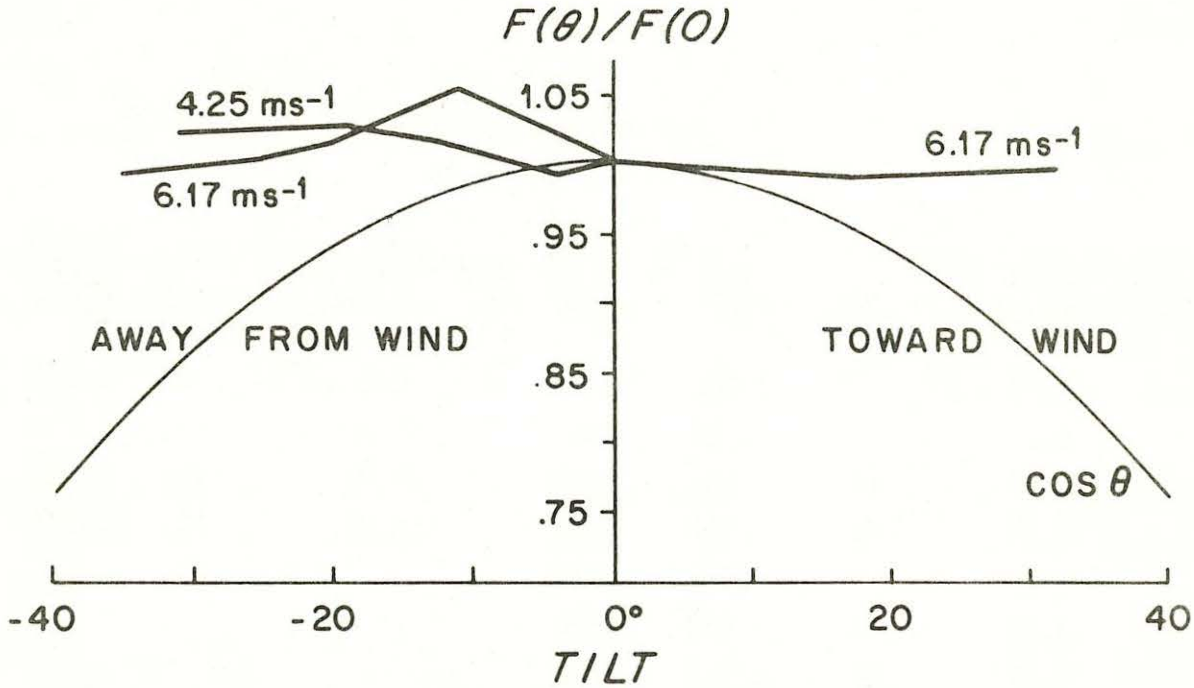


Figure 7. VAWR tilt sensitivity.

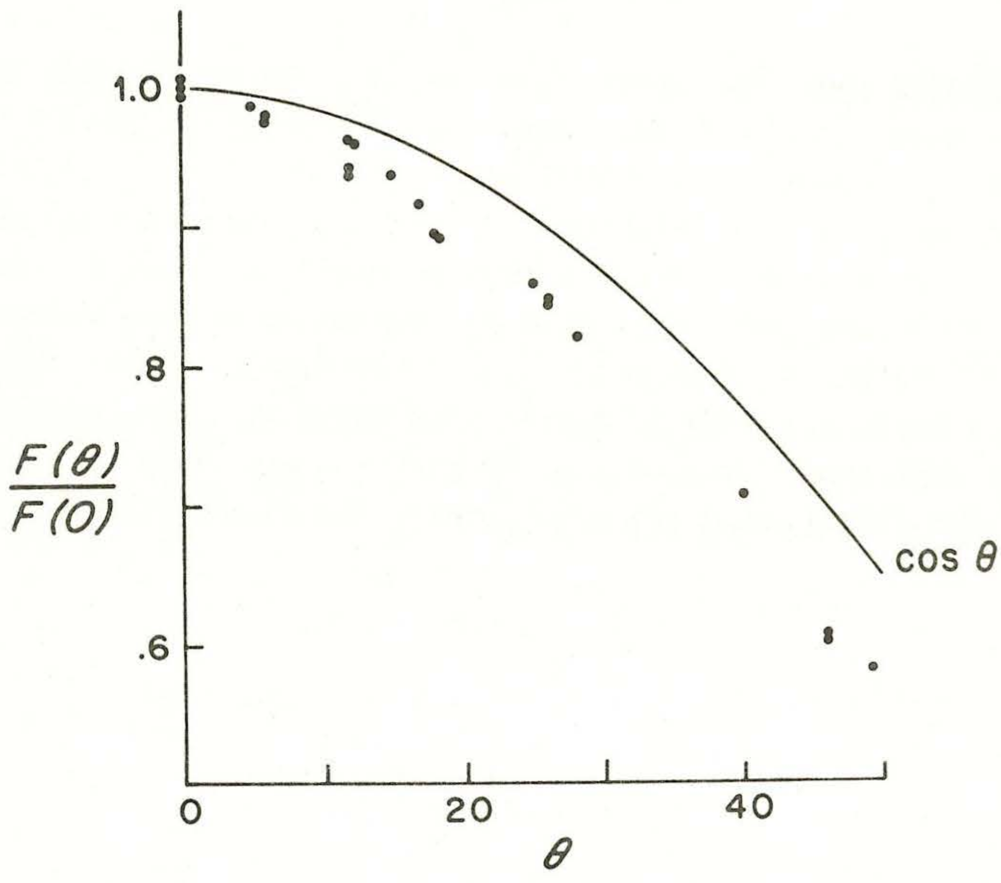


Figure 8. VMWR tilt sensitivity.

Table 7
Inclination Sensitivity
VMWR - Weller Sting with Lexan Propellers
Run Number 19

Lower Propellers				Upper Propellers			
Wind Speed	Incl.	$\frac{F(\theta)}{F(0)}$	Cos θ	Wind Speed	Incl.	$\frac{F(\theta)}{F(0)}$	Cos
2.7 ms^{-1}	0°	1.004	1.000	2.7 ms^{-1}	0°	1.000	1.000
2.7	12	.959	.978	2.7	6	.975	.995
2.7	18	.896	.951	2.7	12	.940	.978
2.7	28	.816	.883	2.7	18	.897	.951
2.7	40	.705	.766	2.7	26	.844	.899
2.7	0	.996	1.000	2.7	46	.600	.695
4.7	0	1.000	1.000	4.7	46	.602	.695
4.7	5	.984	.996	4.7	26	.842	.899
4.7	12	.943	.978	4.7	15	.934	.966
4.7	17	.914	.956	4.7	12	.961	.978
4.7	25	.854	.906	4.7	6	.977	.995
4.7	49	.578	.656	4.7	0	1.000	1.000

It is apparent from Figure 8 that the VMWR response drops off much faster with tilt than does that of the other two anemometers. Response has dropped by 5% at about 13°, and by 10% by 20°.

No inclination tests were made of the titanium propellers on the Ciesluk sting.

Azimuthal dependence of VMWR

Weller sting, Lexan propellers

Response was observed at 10° intervals through 90°. Data appear in Table 8 and Figure 9 with values of cos θ for comparison. Data were corrected for deviations from nominal wind speed (maximum deviation was 0.03 ms^{-1}) using the absolute calibration expression.

Table 8
Azimuthal Dependence
VMWR, Weller Sting, Lexan Propellers

Run No.	Wind Speed	Azimuth	$\frac{F(\theta)}{F(0)}$	Cos θ	$\frac{F(\theta)/F(0)}{\text{Cos } \theta}$
9	4.3 ms^{-1}	0	1.002	1.000	1.002
10	4.3	0	.998	1.000	.998
11	4.3	10	.979	.985	.994
12	4.3	20	.919	.940	.978
13	4.3	30	.833	.866	.962
14	4.3	40	.735	.766	.960
15	4.3	50	.605	.643	.941
16	4.3	60	.456	.500	.912
17	4.3	70	.331	.342	.968
18	4.3	80	.163	.174	.937

Weller and Davis (1980) found that the deviation from cosine response was usually between 1.0 and 1.5% of the zero-degree angle of attack response. We found deviations up to 4.4% (60° value) but some of the difference may be due to a poorer quality wind tunnel.

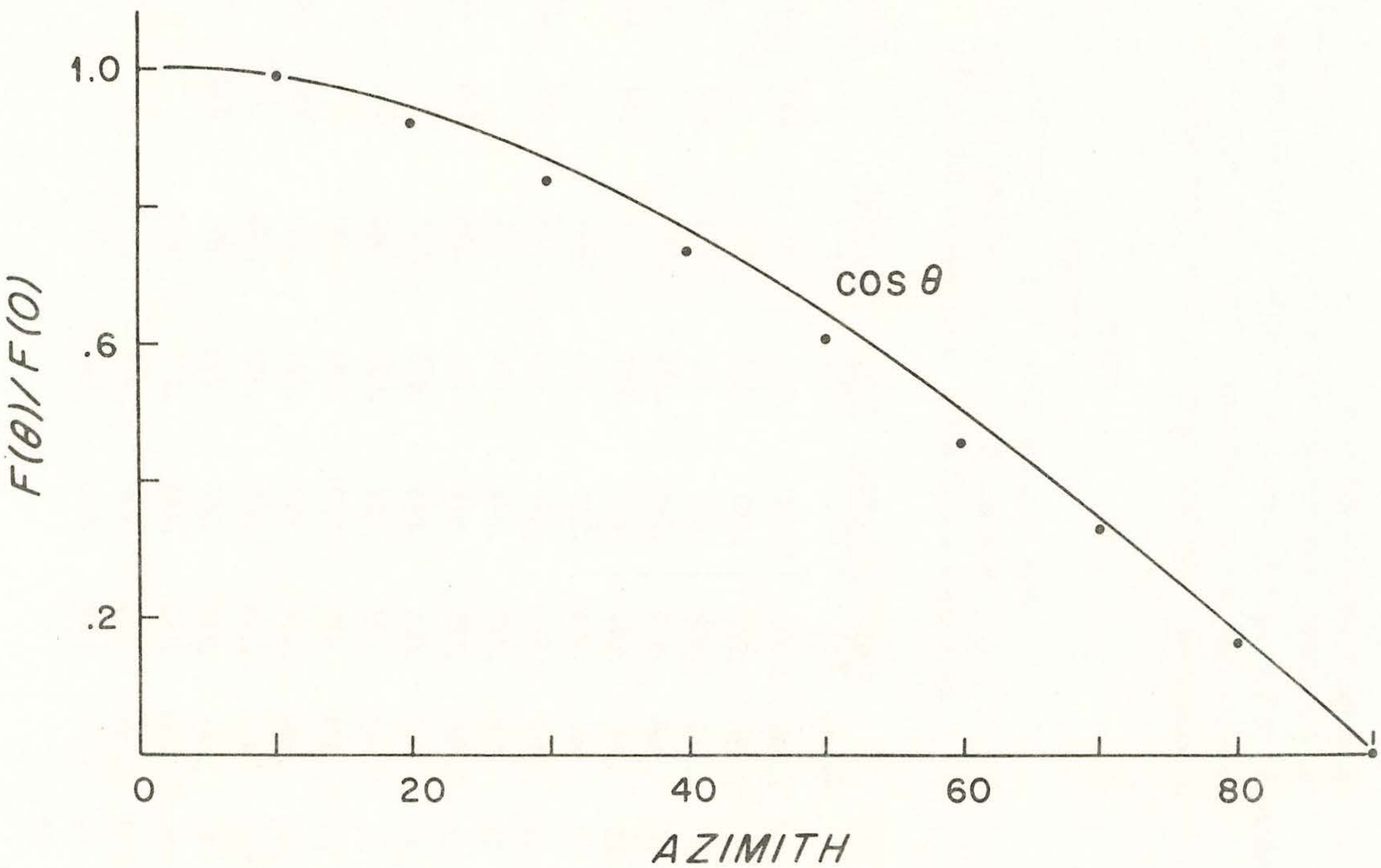


Figure 9. VMWR Lexan propeller azimuthal dependence.

Ciesluk sting, titanium propellers

These measurments were made in more detail than for the Weller sting because the Ciesluk hubs were a modification of the Weller hubs, smoothly rounded but larger and were untested. Frequencies were corrected to the nominal wind speed. The data appear in Table 9 and Figure 10.

Table 9

Azimuthal Dependence

VMWR, Ciesluk Sting, Titanium Propellers

RUN No. 20 — Wind Speed = 4.75 ms^{-1} RUN No. 52 — Wind Speed = 6.60 ms^{-1}

θ	Cos θ	$\frac{F(\theta)}{F(0)}$	$\frac{F(\theta)/F(0)}{\text{Cos }\theta}$	$\frac{F(\theta)}{F(0)}$	$\frac{F(\theta)/F(0)}{\text{Cos }\theta}$	θ	$\frac{F(\theta)}{F(0)}$	$\frac{F(\theta)/F(0)}{\text{Cos }\theta}$
0°	1.000	1.000	1.000	.996	.996	180°	1.004	1.004
5	.996	.988	.992	.987	.991			
10	.985	.959	.974	.965	.980	170	.971	.986
15	.966	.926	.959	.934	.967			
20	.940	.883	.939	.892	.949	160	.903	.961
25	.906	.826	.912	.848	.936			
30	.866	.772	.891	.796	.919	150	.808	.933
35	.819	.720	.879	.746	.911			
40	.766	.671	.876	.688	.898	140	.689	.899
45	.707	.600	.849	.626	.885			
50	.643	.532	.827	.553	.860	130	.556	.865
55	.574	.478	.833	.486	.487			
60	.500	.414	.828	.423	.846	120	.406	.812
65	.423	.349	.825	.359	.849			
70	.342	.283	.827	.293	.857	110	.284	.830
75	.259	.192	.741	.217	.838			
80	.174	.120	.690	.139	.799	100	.130	.747
85	.087	.050	.575	.067	.770			
90								

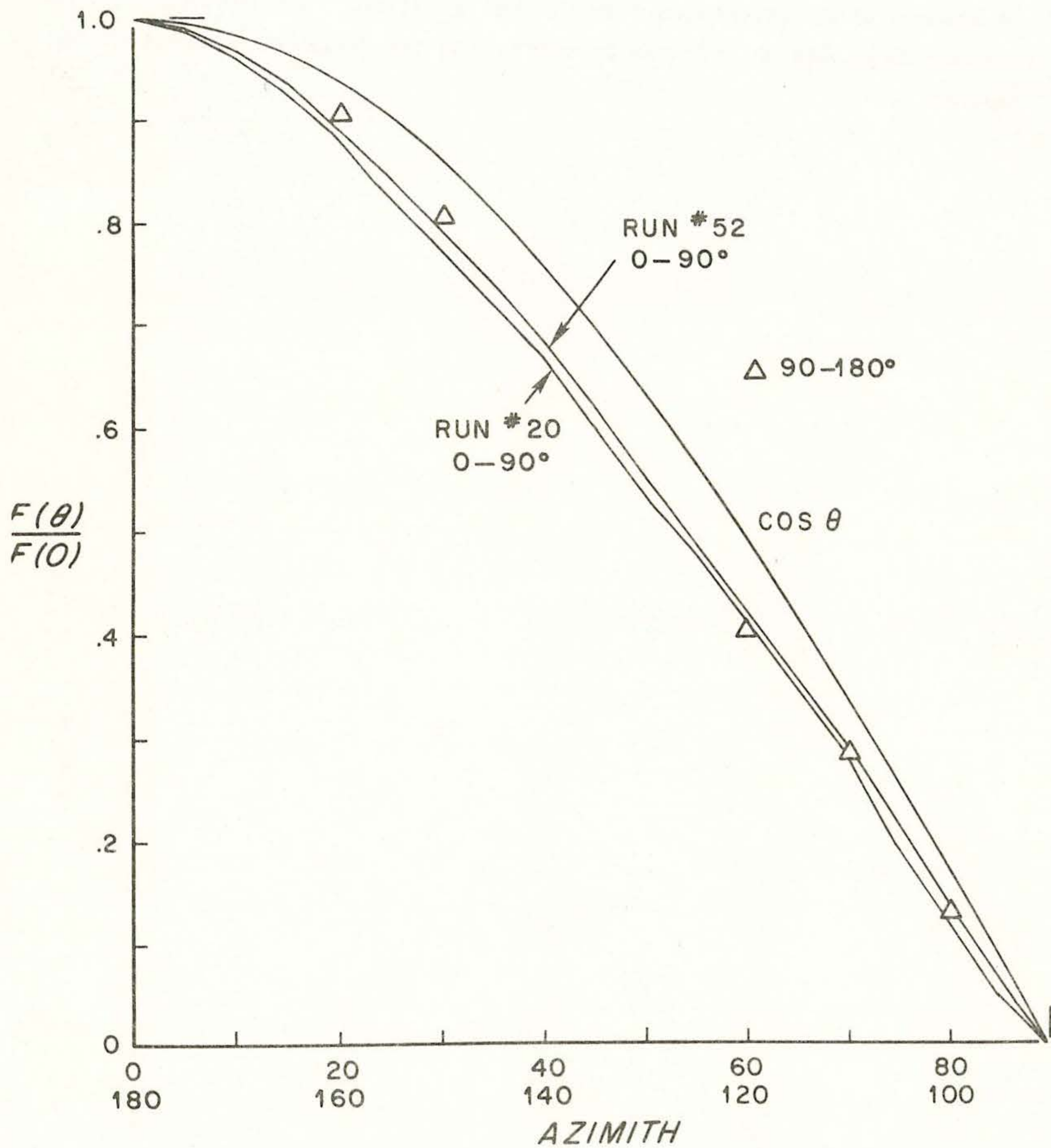


Figure 10. VMWR titanium propeller azimuthal dependence.

It is quite apparent that the Ciesluk sting is not as close to a true cosine response as the Weller sting is. Using a microprocessor-based data logger, that is not a disadvantage but it seems to have no other advantages over the Weller sting. The improvement from Run No. 20 to Run No. 52 made by correcting the propeller separation is apparent.

Distance Constants

In determining distance constants I used the analysis of MacReady and Jex (1964). They assume that the response of rotating wind sensors (cups or propellers) to a change in wind velocity is exponential. Since we have a linear system we can write:

$$F_0 - F = A\, e^{-t/\tau}$$

where:

$F = F(t)$ = rotational frequency of sensor, a function of time

F_0 = equilibrium rotational frequency at wind speed U_0

A = constant, does not have to be determined

t = time from release of cups

τ = time constant of sensor at wind speed U_0

The experimental procedure was as follows:

1. Release the cups or propellers from rest. Initially this was done by holding them still with a fingertip and then releasing. Part way through the runs it was noticed that the presence of a person in the wind tunnel decreased the reading of the pilot tube pressure. This implied a change in wind velocity at the sensor as the person moved away after release so we rigged a 2 m long stick to release the cups. A repeat of several sets of measurements showed that the change in technique made no discernible change in the observed distance constants.
2. Record the pulses on a Sanborne strip chart recorder running at 200 mm/s.
3. Plot $\ell n\ (F_0 - F)$ vs. t.
4. Determine slope at $F = F_0/2$ as recommended by MacReady and Jex (1964). Variation of slope over one run was as much as a factor of two, slope increasing with time (smaller distance constant).
5. Compute distance constant, L_0, from τ by

$$L_0 = U_0\, \tau$$

All distance constant measurements were performed in September 1980 in the 5x7WT.

Gill

We included the Gill cups (Model 6101) partly to reassure ourselved that we were getting reasonable results. R. M. Young Co. states the distance constant as approximately 3.7 m. Table 10 lists our results.

Table 10
Gill cups (R. M. Young Co. Model 6101)
Observed Distance Constants

Run No.	U_0	L_0
42	4.73 ms^{-1}	3.2 m
43	4.73	3.5
44	4.71	3.4
45	2.76	3.4
46	2.76	3.6
47	2.76	3.8
		3.5 ± .2

This is quite reasonable relative to the R. M. Young value and gives us confidence in our values for the other sensors.

With the chopper disc giving us 10 counts per revolution we had excellent resolution to get reliable distance constants.

VAWR

Because of two of the physical characteristics of the VAWR cups, the observed distance constants provide only an approximate upper limit. The long cup arms cause the cup assembly to turn much more slowly than the Gill cups; the VAWR cups produce only one count per revolution. The time constant is of the order of a very small number of turns of the rotors so that the plots of $\ell n(F_0 - F)$ vs. t have few points with substantial scatter. Estimates of the slope vary considerably. The data are shown in Table 11.

Table 11

VAWR Cups Distance Constant

Run No.	U_0	ℓ_0	No. Points
27	2.47 ms^{-1}	12.7	11
28	2.43	13.7	12
29	3.73	16.9	8
30	3.73	14.6	10
31	6.26	5.6	8
32	4.25	1.9	5
34	2.19	2.5	3

The column headed "No. Points" lists how many points were available in each run with which to make the slope estimate and can be considered a measure of how reliable each estimate is. Rejecting Runs 31, 32, 34 as being unreliable, we estimate the distance constant of the VAWR cups as 14.5 ± 2 m. Only the Lexan cups were investigated.

VMWR - Weller sting with Lexan propellers

The VMWR Lexan propellers turned rapidly and had multiple pulses per revolution (four pulses per revolution for the Lexan propellers and two for the titanium). Table 12 lists the data. Distance constant is plotted

Table 12
VMWR - Weller Sting with Lexan Propellers
Distance Constants

Run No.	U_0	L_0
1	1.40 ms^{-1}	9.3 m
2	1.40	9.8
3	2.24	11.1
4	2.34	10.5
5	3.40	11.9
6	3.33	10.6
7	3.40	10.8
8	3.40	11.8
9	4.30	12.2
10	4.28	11.7
48	2.43	10.2
49	2.43	10.5
50	7.31	10.9
51	7.31	10.6
		10.9 ± .8 m

against wind speed in Figure 11. If it were not for the two points at highest wind speed (7.31 ms^{-1}), it would be easy to believe that distance constant increased with wind speed. The 7.31 ms^{-1} data points make it apparent that the distance constant is probably independent of wind speed.

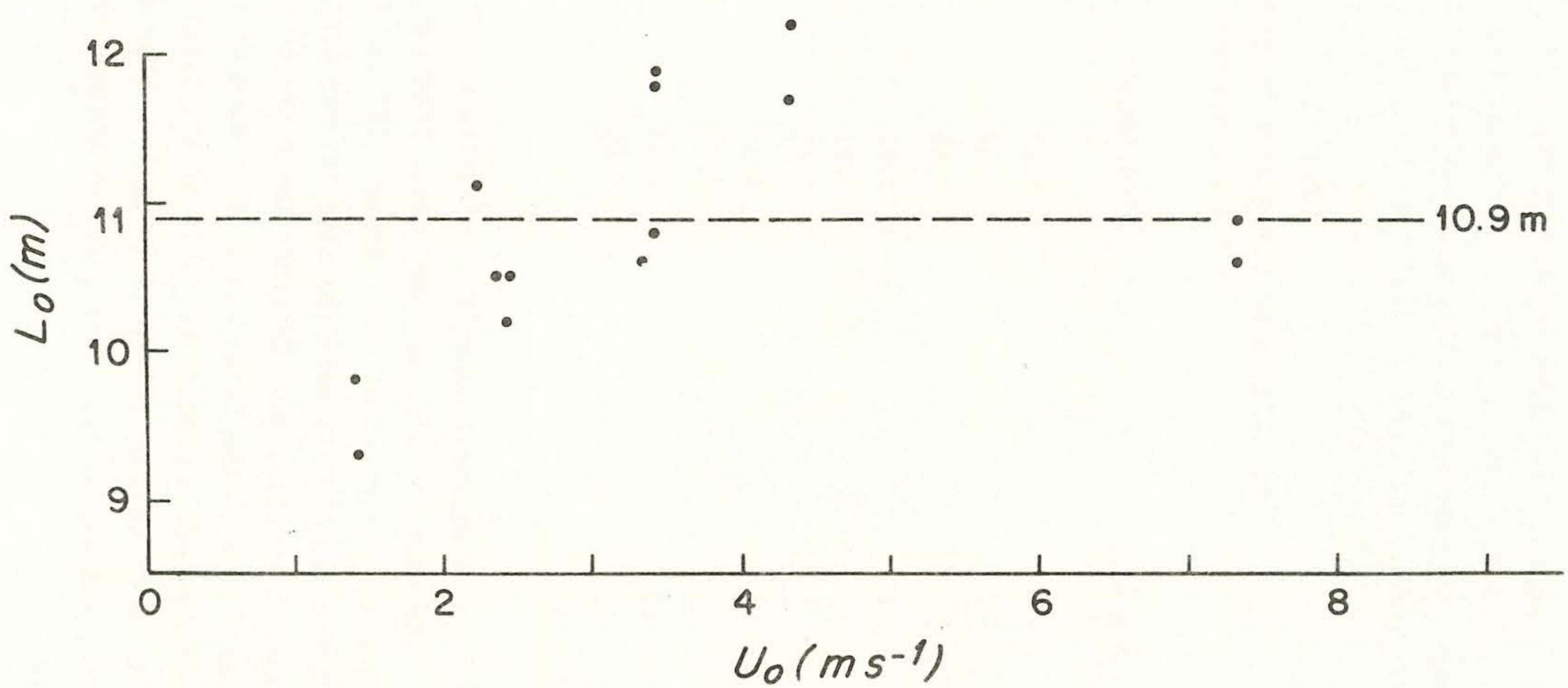


Figure 11. VMWR Lexan propeller distance constant wind speed dependence.

VMWR - Ciesluk sting with titanium propellers

The VMWR titanium propellers produced two pulses per revolution but turned fast enough to produce acceptable resolution. The results of the distance constant runs are listed in Table 13.

Table 13
VMWR - Ciesluk Sting with Titanium Propellers
Distance Constants

Run No.	Wind Speed	ℓ_0
21	4.67	16.7
22	4.67	16.6
23	3.55	16.6
24	3.55	17.6
25	2.51	15.6
26	2.51	16.8
53	4.43	14.3
54	4.43	13.8
55	2.51	14.2
56	2.42	14.1
		15.6 ± 1.4 m

There is no apparent dependence of distance constant on wind speed.

The ratio of distance constants, titanium to Lexan propellers, is 1.43 while the ratio of their masses (144 and 90 gm) is 1.60. If the distribution of mass were the same in both propellers we would expect the moment of inertia, and therefore the distance constant, to be proportional to the total mass. With more of its mass concentrated in the hub we would expect the ratio of the titanium propeller distance constant to that of the Lexan to be less than the ratio of the masses which, indeed, it is. This gives us another reasonableness check on the data.

Azimuthal dependence of distance constant

Since azimuthal behavior of the VMWR propellers is important to their performance, we investigated the azimuthal behavior of the Lexan VMWR propellers' distance constant. Data are listed in Table 14 and shown in Figure 12. Also shown is the function $\sqrt{\cos\theta}$. Brook (1977) and Hicks (1972) found that their data behaved as the function $\sqrt{\cos\theta}$.

Table 14
Azimuth Dependence of Distance Constant
Lexan VMWR Propellers

Run No.	Wind Speed (ms^{-1})	θ	L_0 (m)	$L_0(\theta)/L_0(0)$	$\sqrt{\cos\theta}$
9	4.30	0°	12.2	1.02	1.00
10	4.28	0	11.7	.98	1.00
11	4.33	10	11.9	1.00	.99
12	4.30	20	11.3	.95	.97
13	4.33	30	10.0	.84	.93
14	4.30	40	8.7	.73	.88
15	4.28	50	8.7	.73	.80
16	4.28	60	7.4	.62	.71
17	4.30	70	7.8	.65	.58
18	4.30	80	6.6	.55	.42

Our data only generally follow a $\sqrt{\cos\theta}$ curve.

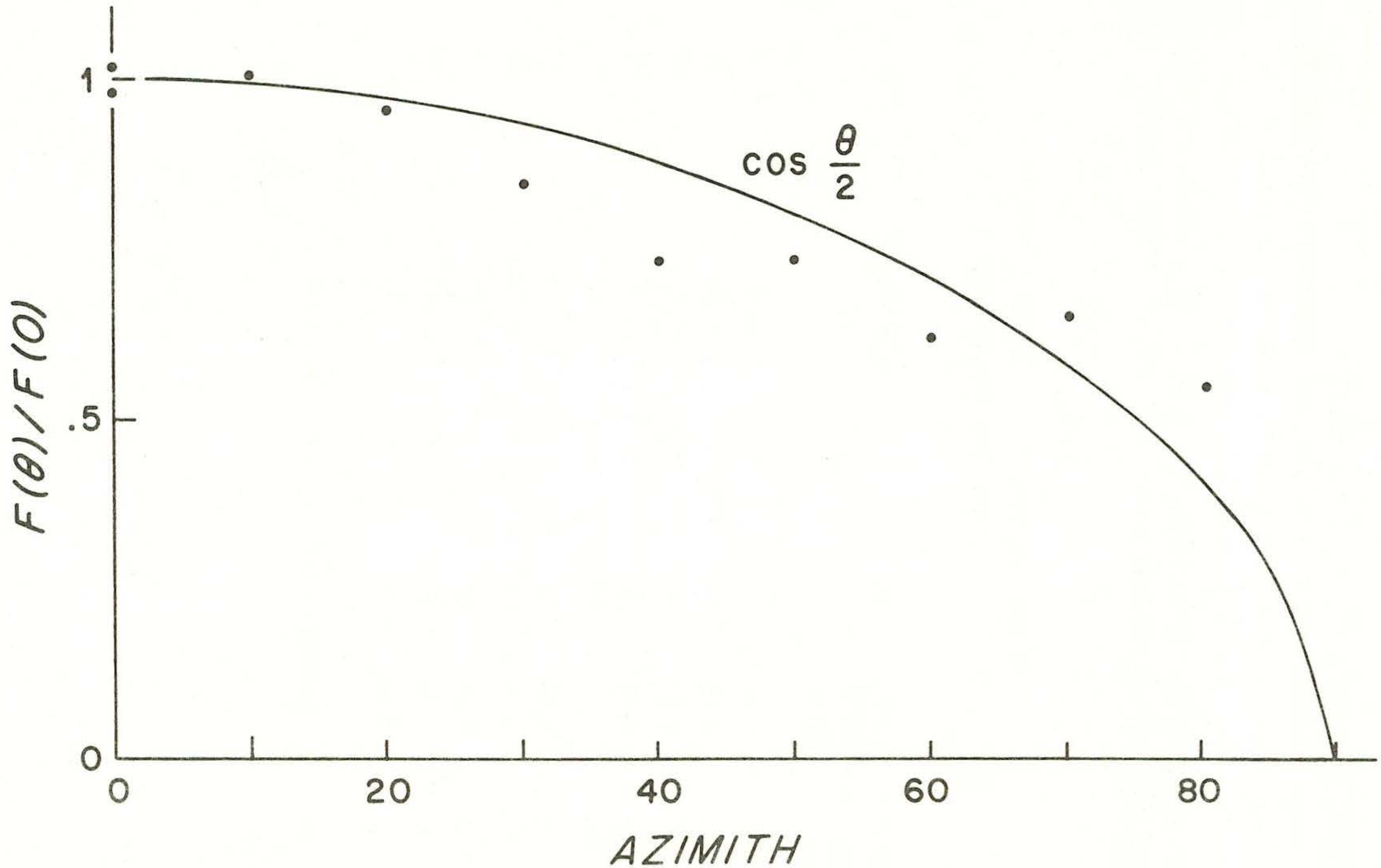


Figure 12. VMWR Lexan propeller distance constant azimuthal dependence.

Dynamic Constants of Vanes

Several runs were made on the Gill and VAWR vanes to measure damping ratios and delay distance. The D/A converter between the vane followers and strip chart recorder was crude and required that we release the vane from an orientation of 90° with the wind stream. An initial orientation of 30° would give more useful results but with our data we can at least make a qualitative comparison of the two vanes.

We used the analysis method described by Camp, Turner and Gilchrist (1970). With the low damping ratios of these two vanes we had to use the first swing of the vane to determine the damping ratio. In this case the damping ratio is defined by

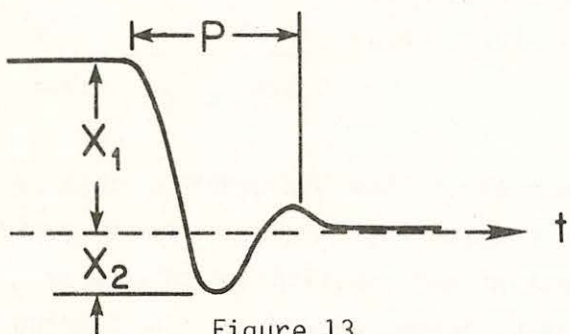


Figure 13

Damping ratio and delay distance experiment parameters

$$h = \frac{1}{\{1 + [\pi/\ \ell n(x_1/x_2)]^2\}^{1/2}}$$

and the damped period by

$$F_D = P^{-1}$$

where x_1, x_2, P are as shown in Figure 13.

The natural frequency of the vane is given by

$$F_n = \frac{F_D}{(1 - h^2)^{1/2}}$$

and the delay distance by

$$D = \frac{U_0}{2\pi F_n h}$$

where U_0 is the tunnel equilibrium wind speed. The damped and natural wavelengths.

$$\lambda_D = \frac{U_0}{F_D} \ ; \quad \lambda_n = \frac{U_0}{F_n}$$

as well as the damping ratio and delay distance should be independent of tunnel wind speed.

Gill vane

The measured and computed quantities for the four Gill vane runs are shown in Table 15.

Table 15

Gill Vane Parameters

Run No.	U_0	x_1	x_2	h	P	F_D	F_n	D	λ_D	λ_n
62	9.61	90°	27.0	.659	.870	1.16	1.53	1.52		
63	9.61	90	23.4	.679	.805	1.24	1.69	1.33	7.7	5.7
64	13.99	90	23.4	.679	.590	1.70	2.31	1.42	8.3	6.1
65	13.99	90	23.4	.679	.570	1.75	2.39	1.37	8.0	5.9
				.67				1.4	8.0	5.9

For the Model 6301 vane R. M. Young Co. states the damping ratio is about 0.37. Our value of about 0.7 is considerably higher. The increase is difficult to explain since the effect of our substitution of a Gray coded binary disc for the potentiometer on moment of inertia and damping should have been negligible. Our high value may be partly due to the large initial displacement.

R. M. Young Co. does not state values for the other parameters for this vane but does for the Model 12302, the same design and dimensions but with a styrofoam tail substituted for the sheet aluminum tail. Stated delay distance for the Model 12302 is 1.0 m while our value for the Model 6301 is 1.4 m. This is reasonable considering the increased mass (1.1 kg for the Model 1230; 1.4 kg for the Model 6301).

The Model 12302 damped natural wavelength is 2.5 m; our value for the Model 6301 is 8.0 m, again reasonable.

The Model 12302 theoretical undamped natural wavelength is 4.8 m; the Model 6301 is 5.9 m, reasonable.

Our measurements on the Model 630 then show that it is a little slower to respond due to its increased mass over the Model 12302. Our values, however, lack accuracy because of the crude recording equipment and the resulting necessary large initial vane displacement.

VAWR Vane

The measured and computed quantities for the four VAWR vane runs are shown in Table 16.

Table 16

VAWR Vane Parameters

Run No.	U_0	x_1	x_2	h	P	F_D	F_n	D	λ_D	λ_n
58	7.07	175	27.0	.78	1.175	.85	1.37	1.05		
59	7.07	90	23.4	.54	1.205	.83	.99	2.10	8.5	7.2
60	12.77	90	23.4	.62	1.195	.84	1.06	3.10	15.3	12.0
61	12.77	90	23.4	.59	1.173	.85	1.30	2.66	15.0	9.8
				.58				2.6		

The VAWR vane is so different from normal meteorological vanes that we have no basis of comparison for judging the data. The fact that the delay distance and natural wavelength are almost double the values computed for the Gill vane is surprising. The horizontal dimensions are so much smaller we would expect the VAWR vane to respond to smaller dimension fluctuations. The appropriate conclusion probably is that the VAWR vane is not suitable for deployment in wind recorders.

Summary

Of the four sensor sets we tested, the Gill cups and vane, the Lexan VMWR propellers, the titanium VMWR propellers, and the VAWR cups and vane, none was an obvious choice as the buoy sensor set. To sum up the results of the tests:

Speed calibration

Gill, both VMWR propellers - adequate

VAWR - turns too slowly

Inclination

Gill and VAWR - ±5% for ±20° tilt

VMWR - ±10% for ±20° tilt

Distance constant

Gill - 3.4 m

Lexan VMWR - 10.9 m

Titanium VMWR - 15.6 m

VAWR - 14.5 m

Vanes

Gill - delay constant = 1.4 m, damping factor = .67, natural wavelength = 5.9 m

VAWR - delay constant = 2.6 m, damping factor = .58, natural wavelenth ≅ 10 m

Leaving questions of mechanical durability aside, the Gill is the preferable set by the factors tested.

Part II. 1980 Beach Intercomparison

Introduction

In summer 1980, a test frame was built on the shore of Nantucket sound at the end of a small pier about 75 feet from shore. The frame faced westsouthwest. When the wind was from the prevailing direction, southwest, it approached the frame over several miles of open water, ensuring a turbulence field similar to that over open ocean. In this section name wind directions will be meteorological convection while numbers on plots will be oceanographic convection.

We mounted three instruments on the test frame during three different time periods. Winds and instruments cooperated to give us totally useful data during only one of these periods, 1-8 August. During that time the following instruments were mounted on the test frame:

1. The original VAWR with light weight Lexan cups (see Figure 1, in first section of report).
2. A VMCM used as a wind recorder (see Figure 2).
3. An R. M. Young Company utility wind vane and three cup anemometer (to be referred to as the "Gill set" since they were designed by G. C. Gill, see Figure 3) attached to a set of VACM electronics. The cup anemometer was modified so that the rotations were sensed by a Sony magnetodiode and the wind vane so that its azimuth was sensed by a Gray-coded binary disc and light block. These modifications made the sensors compatible with the VACM electronics.

The data extends from 2000Z on 1 August to 1300Z on 8 August. Figure 14 shows the wind speed and direction as recorded by the Gill set during this time. Speeds varied from near zero to about 7 m s^{-1} but the direction was uniformly southwest except for a few brief periods. The Gill vane follower was biased by about +35°. The conditions were quite typical for the south shore of Cape Cod in the summer. The pressure gradient supports a wind from the southwest which is reinforced most afternoons by the sea breeze.

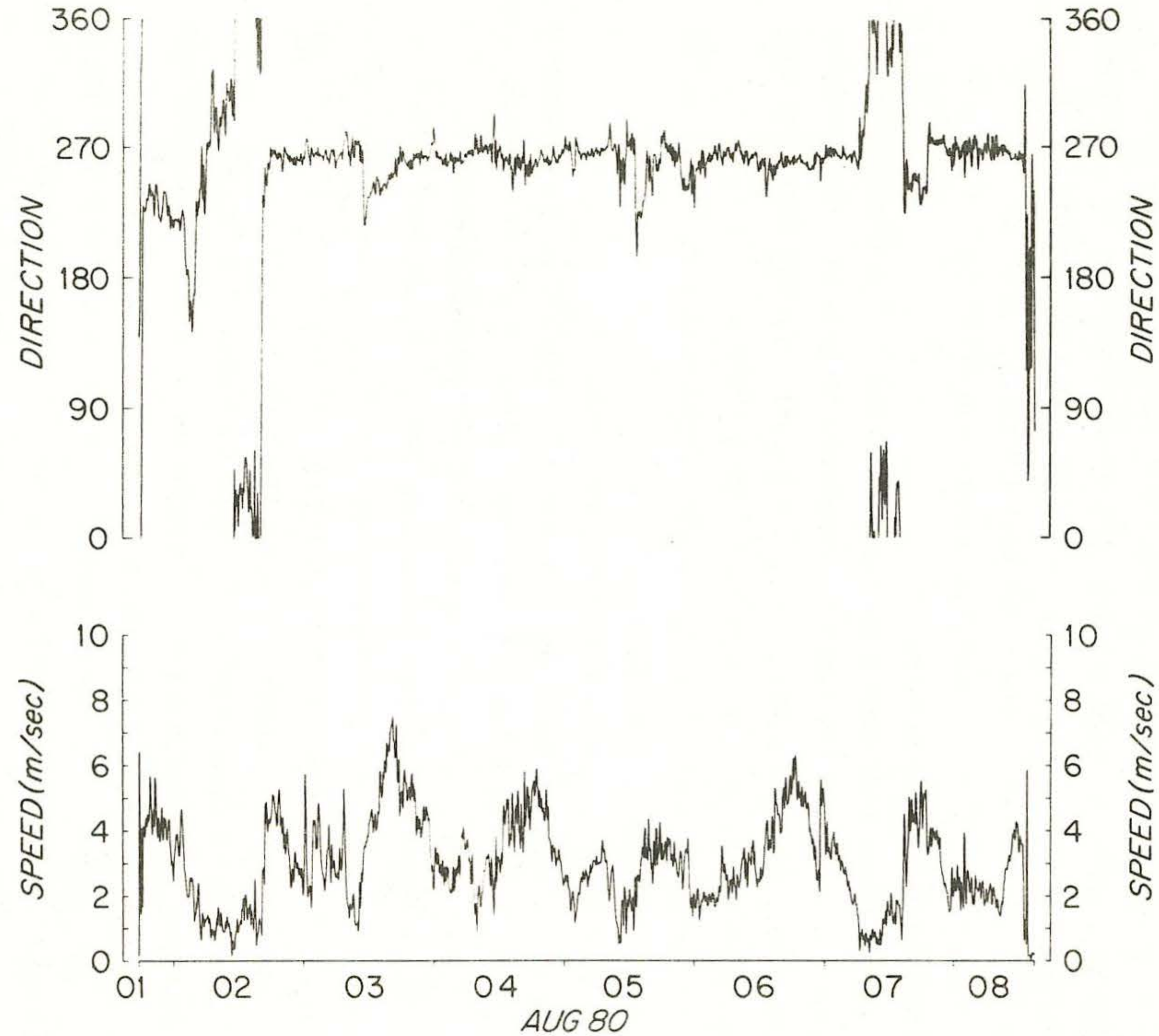


Figure 14. Gill set wind speed and direction, 1980 dock intercomparison.

Wind Speed Intercomparison

Figure 15-17 are scatter plots of the vector averaged speeds from the three instruments. Vane performance affects these speeds to a small degree but primarily the plots reflect the performance of the wind speed sensors.

VMWR vs. Gill set -- Figure 15.

The equation of the linear regression is:

$$S_{VMWR} = -.17 + 1.037\ S_{Gill}$$

with a standard error of 0.12 m s^{-1}. The equations used for decoding the data were, for the VMWR,

$$S_{VMWR} = .375\ F,$$

the equation determined by Weller (personal communication) in water calibrations; and for the Gill anemometer,

$$S_{Gill} = .2 + .75\ F$$

where F is the rotational frequency of the sensor. We used a bias of 0.2 m s^{-1} for Gill as indicated by our wind tunnel tests rather than the manufacturer's value of 0.3 m s^{-1}.

The linear regression implies that the VMWR should have the same bias as the Gill anemometer, 0.2 m s^{-1}. This is reasonable since they both contain precision ball bearings. Adding this bias to the VMWR equation means that speeds from the instruments agree within 4% .

VAWR vs. Gill set -- Figure 16

The equation of the linear regression is:

$$S_{VAWR} = .50 + .862\ S_{Gill}$$

with a standard error of 0.15 m s^{-1}. The equation used for decoding the VAWR data was,

$$S_{VAWR} = .85 + 1.75\ F.$$

The agreement of the VWMR and Gill wind speeds implies that both calibration equations are correct. Figure 16 then implies that both bias

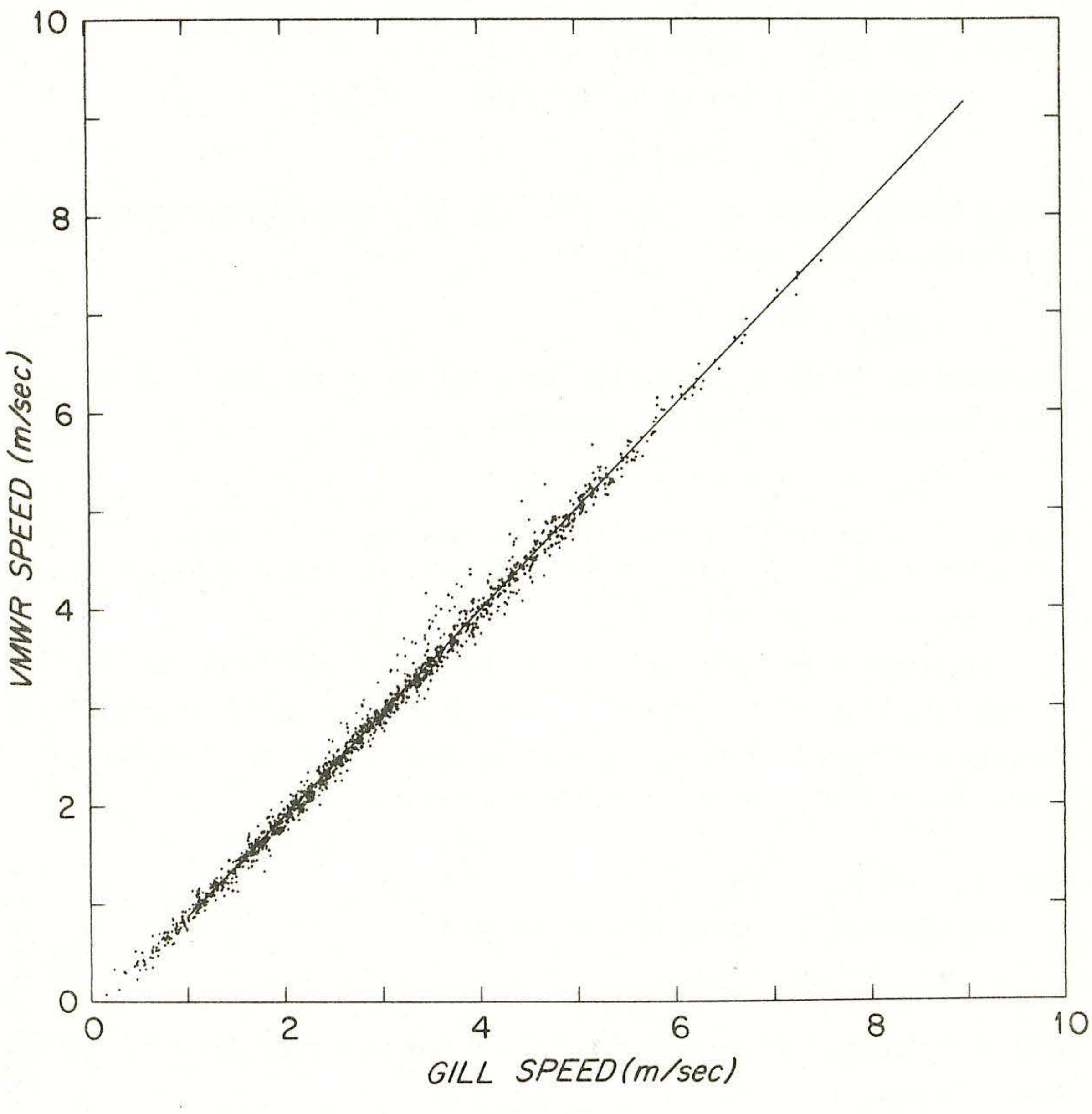


Figure 15. VMWR vs. Gill set vector averaged speeds.

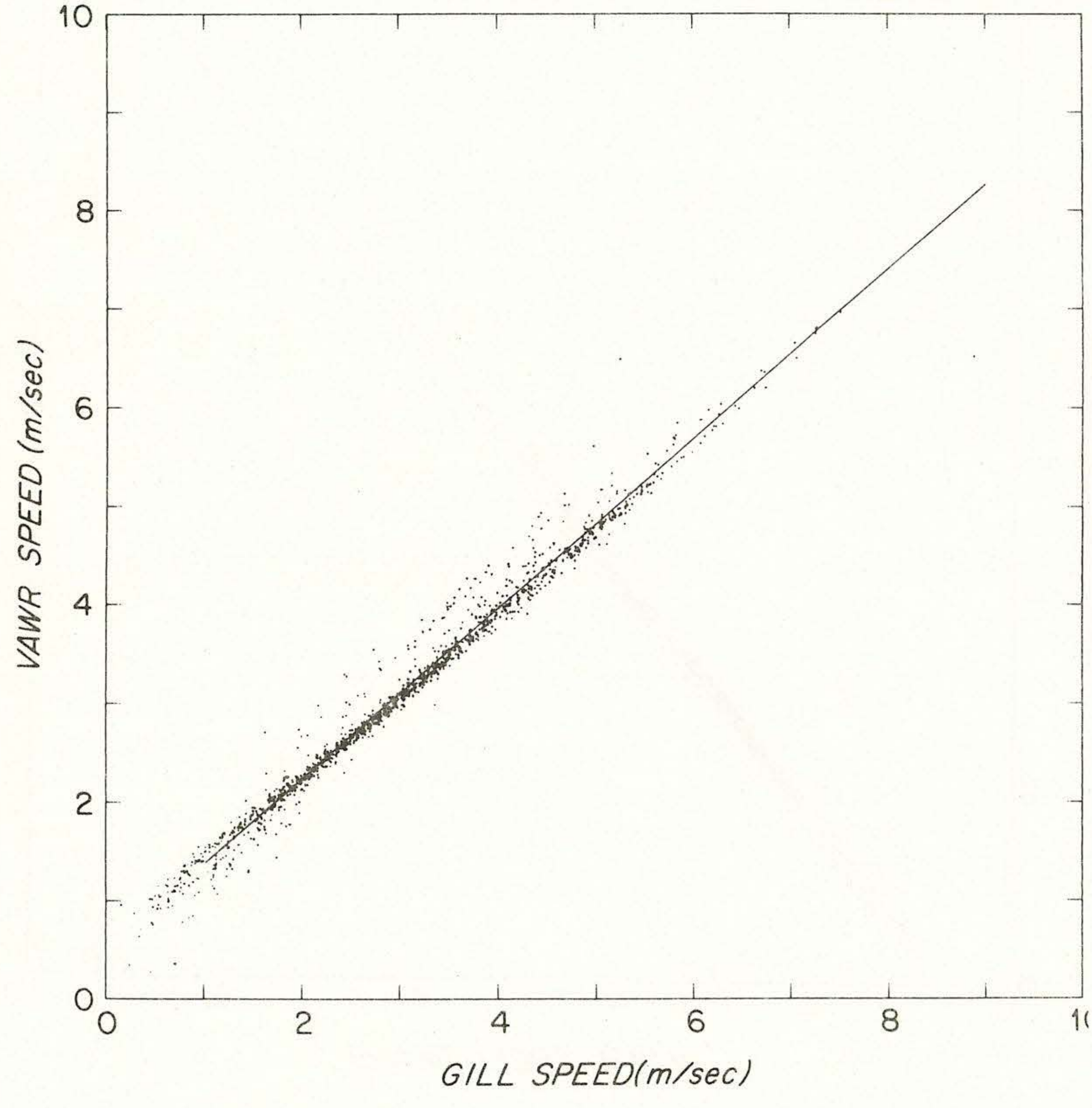


Figure 16. VAWR vs. Gill set vector averaged wind speeds.

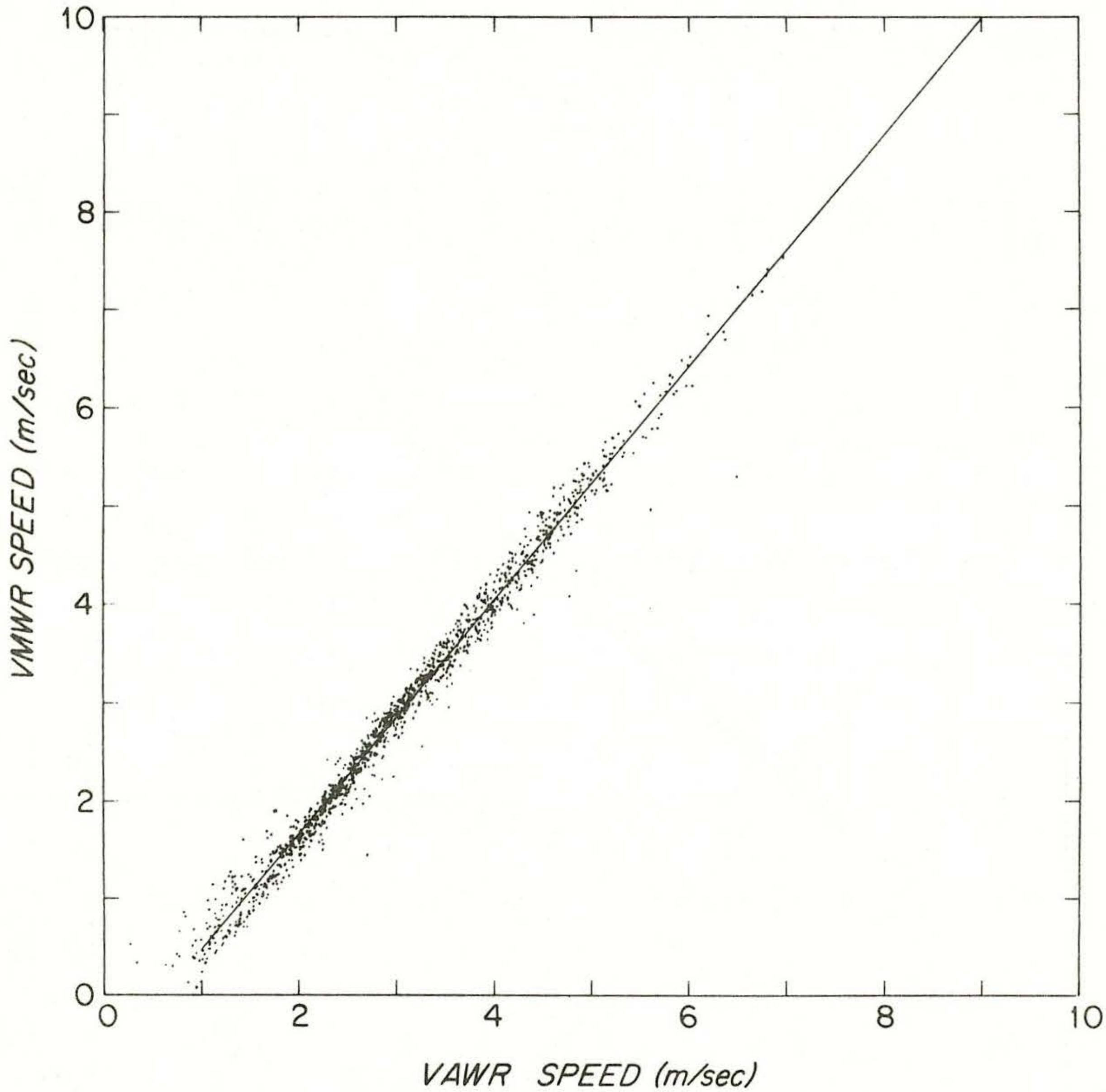


Figure 17. VMWR vs. VAWR vector averaged wind speeds.

and slope are too large in the VAWR equation above, and that the VAWR equation should be:

$$S_{VAWR} = .4 + 2.03\ F.$$

VMWR vs VAWR -- Figure 17

The equation of the linear regression is:

$$S_{VMWR} = -.73 + 1.191\ S_{VAWR}$$

with standard error 0.17 m s^{-1}. Assuming that the revised VMWR calibration equation given earlier in this section is correct implies that the VAWR calibration equation should be:

$$S_{VAWR} = .3 + 2.08\ F.$$

These two VAWR calibration equations resulting from the beach intercomparison are difficult to reconcile with the wind tunnel calibrations. In Table 1, summarizing all the VAWR wind tunnel calibrations, there is no bias less than 0.5 m s^{-1} and no slope greater than 1.77. Since the VMWR and Gill anemometer wind tunnel calibrations also disagree with the Weller and R. M. Young Company calibrations, respectively, and by different amounts, it is hard to escape the conclusion that the wind tunnel calibrations are not valid.

Overspeeding

It is apparent on each of Figures 15-17 that there are more points on one side of the regression than on the other which are well separated from the line. An explanation consistent with the data is that these points result from overspeeding. If we assume that the value of the standard errors of the linear regressions result primarily from overspeeding sensors then the Gill overspeeds the least, the VMWR the next most, and the VAWR the most.

Wind Direction Intercomparison

Figure 18 shows plots of the vector averaged wind direction as measured by the Gill set and the three possible direction differences between instruments. Compasses and vanes were not aligned carefully in the

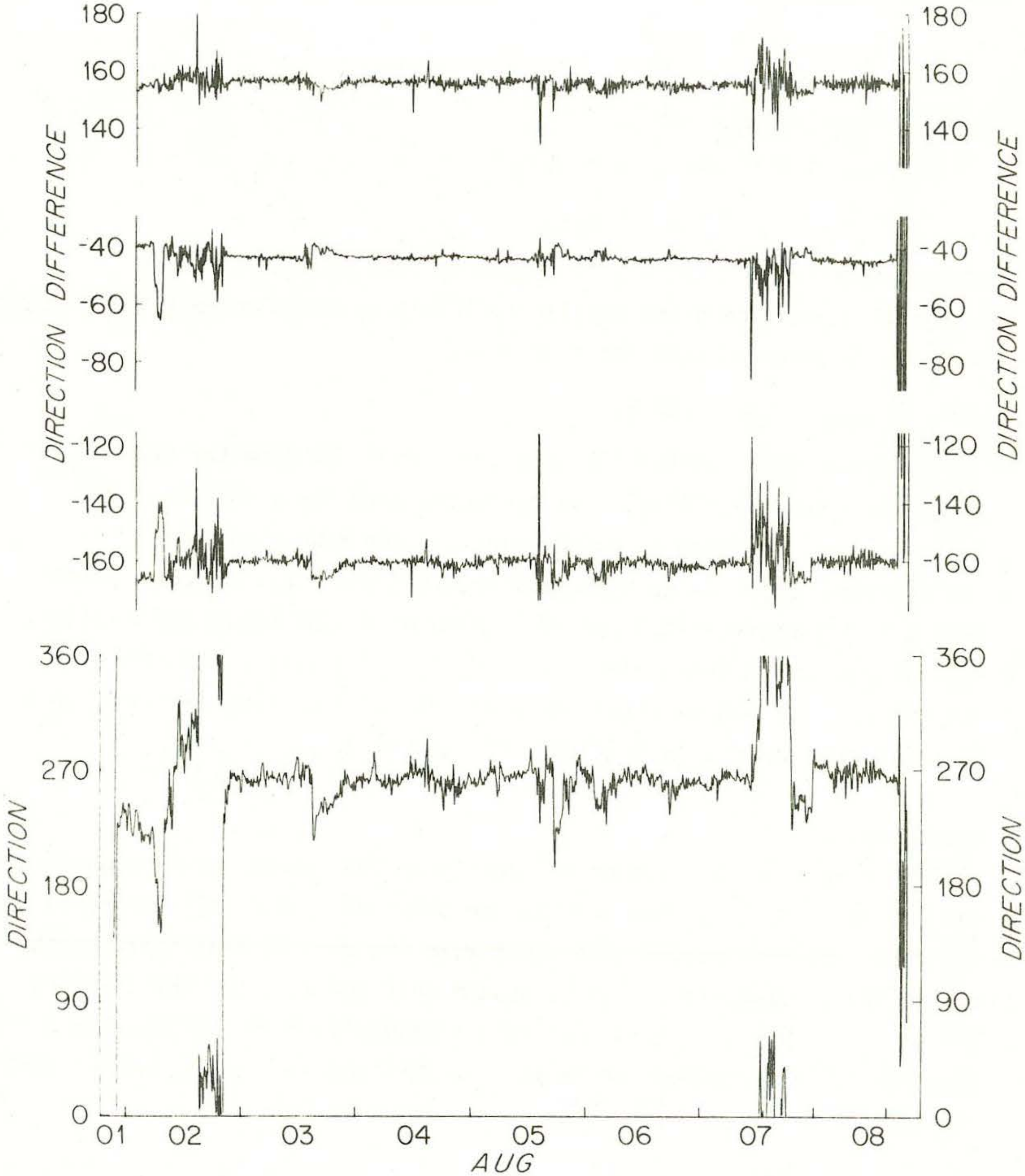


Figure 18. Wind direction and direction differences.

instruments before deployment. The differences fluctuate about a bias value different from zero because of this.

The smallest differences are between the VMWR and Gill directions and seem to be relatively independent of wind shifts. The VAWR, however, does not seem to track wind shifts as well as the other two sensor sets. For example, early on 2 August the wind shifts from south to east and back to south within about two hours. The VAWR sees the shift as being 25° less than the other two intruments.

At midday on 5 August the wind shifts about 90° in about 22 minutes and then half way back in one recording interval (7.5 minutes). Again the VAWR does not seem to track the other two instruments as well as they track each other. We think that these differences probably were caused by the wakes of the other two instruments. The VAWR was the westernmost instrument on the platform and both wind shifts started in the southwest and shifted toward the east.

We believe that this set of data will not support any statements about the relative merits of the three direction sensing techniques.

Summary

The speed intercomparison from the 1980 beach data calls into question the speed calibrations done in the M.I.T. wind tunnels. For both the Gill anemometer and the VMWR it is probably preferable to accept the manufacturer's calibration than to accept the wind tunnel calibrations.

The effects of the smaller distance constant of the Gill cups is apparent in the data.

Within the limits of this test, the direction measurements of the three sensor sets are equivalent.

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Summaries of performance data on three wind recorder sensor sets are presented. These include a W.H.O.I.-built vane and cup set mounted on a vector averaging current meter (VACM), a pair of orthogonal propellers (the vector measuring current meter, or VMCM), and an R. M. Young Company utility wind set connected to a VACM set of electronics. All three instruments vector average the observations continuously.

Absolute calibrations of the speed sensors as a function of wind speed and inclination and measurements of distance constants of speed sensors and vanes are described. These measurements were made in two wind tunnels at the Massachusetts Institute of Technology.

An intercomparison of the three instruments on a test stand on the shore of Nantucket Sound is also described.

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